A smooth path or a bumpy ride?

an analysis of the transitory phase of environmental regulation

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An Analysis of the Transitory Phase of Environmental Regulation

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Abstract

This paper gives an analysis of the transitory phase of regulation between the introduction of regulation and the reaching of an equilibrium. Four instruments, absolute and relative standards and permit and credit trading are discussed and both the scenario where the standards are adjusted in every time period and where the are set at their long-run level are considered under both perfect and imperfect competition. It is shown that environmental regulation can lead to high and persistent volatility in the markets, especially under credit trading and relative standards and when standards are adjusted regularly. Volatility is also more likely under imperfect than under perfect competition. Setting a constant standard may lead to a longer transitory phase.

1 Introduction

In modelling environmental regulation, it is usually assumed that firms and the industry as a whole adjust instantaneously to the new regulation and move to the new equilibrium. The transitory phase is not modelled and it is implicitly assumed that the path to the new equilibrium is a smooth one. The fact that this phase is not modelled could be interpreted as implying that this path is not important and that the transitory phase is just that, something that will go away. The new equilibrium will arise and it is this outcome we are interested in.

However, the transitory phase is of importance and needs more attention. If the path to the new equilibrium is rather volatile, firms will incur costs from the uncertainty that surrounds them. Prices observed now need not be a good prediction of prices in the future. Hence, the efficiency of an instrument also depends on how fast and how smooth it gets the industry from no regulation to the new equilibrium with regulation. That is, if the industry reaches the new equilibrium at all. It is possible that the path embarked on with the implementation of regulation is so volatile that the industry never settles down in an equilibrium.

This paper explicitly models the transitory phase for four instruments, absolute standards, relative standards, credit trading and permit trading, in both a perfectly and an imperfectly competitive industry. For that purpose, a dynamic model is developed in which firms can enter or exit the market, depending on the profitability of the incumbent firms. Two scenarios are analyzed. In the first scenario, the standard that will hold in the equilibrium with regulation is set from the first period. In the second scenario, environmental policy is revised in every period according to the situation in the previous period. Relative standards are defined as allowed emissions per unit of output. Since total output can change in every period, the standard has to be adjusted to realize the emission target. The same holds for credit trading since this form of emissions trading is based on relative standards. With absolute standards, the quantity of allowed emissions per firm will have to be adjusted with entry or exit. For emissions trading, no such adjustment is needed, since there exists a ceiling on total emissions which is realized in every period.

This paper builds on work by Dijkstra (1999) and Boom and Dijkstra (2006). Dijkstra (1999) analyzes the effect of different instruments on a perfectly competitive industry, given that the government wants to achieve a certain abatement level. He shows that different instruments have different impacts on the industry, with relative standards leading to the highest output level and permit trading with grandfathering leading to the highest profits. These results clearly have implications for the political acceptability of the different instruments. Boom and Dijkstra (2006) gives a model of permit and credit trading, analyzing both perfect and imperfect competition (see also Fischer 2001 and Gielen et al. 2002). Boom and Dijkstra (2006) shows that the two types of emissions trading have different impacts on the industry. The specific model used in Boom and Dijkstra (2006) is also used in this paper.

This paper is organized as follows. In the next section, the model is developed. Sections 3 and 4) present the regulation scenarios and simulation results for perfect, respectively imperfect competition. Several cases are given to illustrate the effect of regulation on the industry. In Section 5 some general conclusions are given.

2 The Model

Consider an industry, consisting of n firms that produce a homogeneous good. Production per firm is given by q and the price of the good is p. In producing the good, firms emit a pollutant E, which the government wants to regulate. The overall goal of the government is to limit total emissions to the level L.

Firm costs are given by

$$C(q, E) = aq^2 + b(q - E)^2 + K \tag{1}$$

Here, a and b are parameters and K gives fixed costs, with $a, b, K > 0$. For this cost function, it holds that $C_q > 0$, $C_{qq} > 0$, $C_E < 0$, $C_{EE} > 0$, $C_{qE} = C_{Eq} < 0$.

The inverse demand function is linear and is given by

$$p = \alpha - \beta nq \tag{2}$$

with $\alpha, \beta > 0$.

In the following, I will analyze the effect of four forms of environmental regulation on the industry; permit trading, credit trading, relative standards and absolute standards. Under permit trading, the government divides the total emission ceiling in permits and distributes these over the polluters, either by grandfathering or auctioning, after which the polluters can trade the permits. With credit trading, the government sets a relative standard that limits emissions per unit of output. Firms that can stay below this relative standard can sell credits. Absolute standards set a ceiling on emissions per firm. I will first discuss the case when there is perfect competition, and then when there is imperfect competition in the industry. In both cases, the necessary models are developed after which they are used to generate simulations that show the functioning of the instruments under different circumstances.

We analyze two forms of government behavior; myopic behavior and perfect foresight. With perfect foresight, the government knows the optimal long-run standard under credit trading and relative and absolute standards. The government then implements this long-run standard from the start. With permit trading, the government does not set a standard, so here the type of foresight of the government does not matter. With myopic behavior, the government sets its policy in each period based on information from the previous period. Hence, with absolute standards, the government sets the limit on emissions per firm at time t, $\bar{E}_t$, by dividing the limit on total emissions by the number of firms in the previous period:

$$\bar{E}_t = L/n_{t-1} \tag{3}$$

With permit trading, there are two possibilities. One possibility is that the government hands out permits every period to firms that produced output in the previous period, so that $\bar{E}_t$ is given by (3). This implies that new entrants will have to buy their way into the market. Firms that exit sell their permits and cease to exist, where exiting firms are defined as those that set output equal to zero. Alternatively, the government could auction the permits at the beginning of every new period. Both ways of distributing will give the same outcome in the model. With perfect foresight, the government sets the long run equilibrium values of the different instruments from the start of the regulation program. Combined trading does not alter the way the government sets its policy.

With relative standards and credit trading, the relative standard is given by the emission limit divided by total output in the previous period:

$$\bar{e}_t = L/(n_{t-1}q_{t-1}) \tag{4}$$

Although an equilibrium can be derived, especially under perfect competition (see Boom and Dijkstra (2006)), exit and entry of firms is used to create dynamics in the system. Exit and entry are modelled similarly, but slightly differently under perfect and imperfect competition. In both cases, entry (exit) occurs in period t when there are positive (negative) profits in period $t-1$. Then for perfect competition, let the number of firms in the sector at period t be

$$n_t = n_{t-1} + \gamma \left(\frac{Q_{t-1}}{q_{t-1}^{min}} - n_{t-1} \right) \tag{5}$$

Here $\gamma > 0$ gives the rate of adjustment and q^{min} is the output level at which a firm earns no profit. That is, q^{min} is the level of output where marginal costs are equal to average costs, where costs include both operating costs and all costs of regulation. It should be noted that the q^{min} calculated in this way does not necessarily give the long-run output level. It gives the lowest cost output level taking present regulation as given. Specifically, in calculating q^{min}, the absolute or relative standards are taken as given or the permit price (both under permit trading and combined trading) is taken as given. If present regulation is not at its long-run equilibrium level, then neither will q^{min} be.

Using (5) implies that entry will happen when profits are positive, while there will be exit when profits in the industry are negative. To see this, note that when firms make a profit, their output is higher than q^{min}. Equation (5) says that firms will enter (exit) when output per firm is higher (lower) than q^{min}. Using (5) has the advantage that it can be readily seen how fast firms adjust. So when $\gamma = 1$, firms adjust fully in the sense that if policy does not change, entry or exit will be such that, in the next period, profits are zero in the industry. Setting $0 < \gamma < 1$ then gives slower than full adjustment, while $\gamma > 1$ gives more than full adjustment (or over-adjustment).

The number of firms in the industry is an integer. However, (5) does not necessarily give an integer. To deal with this problem, the number of firms found through the use of (5) is rounded down to the nearest integer.

In the dynamic model of oligopoly, presented in section 4, firms take the output of their competitors as given. More specifically, they assume that the output levels of their rivals will be the same as they were in the previous period. Furthermore, the government sets the relative and absolute standards in the myopic manner as described above under perfect competition. This will be compared with the case were the long-run equilibrium value of the standards is set from the beginning. Under perfect competition the number of firms was assumed to change as a function of profit in the previous period. A similar method was employed under imperfect competition. We assume that firms determine how many firms there can be in the current period. Then entry or exit occurs in the next period up to the level that could have been sustained in the previous period. This is exactly the same as what happens under perfect competition with $\gamma = 1$.

3 Perfect Competition

In this section, the transition from a state without regulation of emissions to a new state with restrictions on emissions is simulated in the case of perfect competition. In subsection 3.1 the discrete time model is given for the various types of regulation. In subsection 3.2, the simulation results of the transition phase are presented and discussed.

3.1 Regulation scenarios

No Regulation. The situation without regulation is the starting point of the analysis and gives a benchmark for the changes caused by regulation. We will assume that the industry is in long-run equilibrium before regulation is introduced. In this case, profits for a firm are, from (1):

$$\pi = pq - C(q, E) = pq - aq^2 - b(q-E)^2 - K$$

The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q} = p - 2aq - 2b(q-E) = 0 \tag{6}$$

$$\frac{\partial \pi}{\partial E} = 2b(q-E) = 0 \quad \Rightarrow \quad q = E \tag{7}$$

Besides these conditions, in the long run it must hold that $pq = C(q, E)$, i.e., there should be no profits:

$$2aq + 2b(q-E) = \frac{aq^2 + b(q-E)^2 + K}{q}$$

Using (7) we find

$$q = \sqrt{\frac{K}{a}}$$

To find the market price of the good, insert this into (6) to find:

$$p = 2a\sqrt{\frac{K}{a}}$$

The total number of firms is found by inserting the market price in (2) and solving for n. This gives

$$n = \frac{\alpha\sqrt{\frac{a}{K}} - 2a}{\beta}$$

The three equations for q, p and n fully determine the equilibrium in the no regulation case.

Permit Trading. With permit trading, the government distributes the total limit on emissions as permits over the firms. Let $\bar{E}_i \geq 0$ be the amount of permits received by firm i. The maximization problem for the firm (suppressing the i's) is, from (1):

$$\begin{aligned}\max_{q,E} \quad \pi &= pq - C(q, E) - R^p(E - \bar{E}) \\ &= pq - aq^2 - b(q-E)^2 - K - R^p(E - \bar{E})\end{aligned}$$

where R^p is the permit price. The first order conditions are given by

$$\frac{\partial \pi}{\partial q} = p - 2aq - 2b(q-E) = 0 \tag{8}$$

$$\frac{\partial \pi}{\partial E} = 2b(q - E) - R^p = 0 \tag{9}$$

In this case, with identical firms, emissions trading will equalize emissions between firms in every period, i.e., $E = L/n$. Using this, and inserting for p from the inverse demand function given in (2), we find

$$q = \frac{2b\frac{L}{n} + \alpha}{2a + 2b + n\beta} \tag{10}$$

In the long run, firms regulated through permit trading will have to cover both their operating costs $C(q, E) = aq^2 + b(q-E)^2 + K$ and the opportunity costs of emissions R^pE. That is, in the long run

$$\pi = pq - aq^2 - b(q - E)^2 - K - R^pE \geq 0 \tag{11}$$

The reason for this is that if the firm does not cover the opportunity costs on emissions, it would be better off closing down and selling the permits.

In the analysis, we use the minimum average costs level of output. This output level is given as the q where $\pi = 0$ in (11). With permit trading, q^{min} is found by setting long-run average costs, including the opportunity costs of emissions, equal to marginal costs:

$$\frac{aq^2 + b(q - E)^2 + K + R^pE}{q} = 2aq + 2b(q - E) \tag{12}$$

Using (9) to eliminate E and solving for q gives

$$q^{min} = \frac{\sqrt{4bK - R^2}}{\sqrt{4ab}}$$

During every period then the number of firms is fixed. Using this, q and $Q = nq$ can be found. From this, the price of the good can be derived using (2).

Credit Trading and Relative Standards With relative standards, the government sets a limit $\bar{e}$ on the emissions per unit of output. The firm is then allowed to emit $\bar{e}q$ in total. With credit trading, the firm is allowed to sell credits if it can stay below the total allowed emission level for the firm. Since we are dealing with identical firms in the model, no trade will take place. Therefore, the analysis of credit trading and relative standards becomes identical, except for the fact that under credit trading there is a credit price R^c, while with relative standards, there is a shadow price. In the following, I will concentrate on credit trading.

Under regulation with credit trading, the firm will maximize, from (1):

$$\begin{aligned}\pi &= pq - aq^2 - C(q,E) - R^c(E - \bar{e}q) \\ &= pq - aq^2 - b(q-E)^2 - K - R^c(E - \bar{e}q)\end{aligned}$$

The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q} = p - 2aq - 2b(q-E) + R^c\bar{e} = 0 \tag{13}$$

$$\frac{\partial \pi}{\partial E} = 2b(q-E) - R^c = 0 \tag{14}$$

With identical firms there is no scope for trading, and all firms will emit up to the allowed amount, i.e., $E = \bar{e}q$. Using this, and inserting for p from (2) we find

$$q = \frac{\alpha}{2a + 2b(\bar{e}-1)^2 + n\beta} \tag{15}$$

In this case, there are two variables that need to be determined, n and $\bar{e}$. As with permit trading, n is determined through (5) with q^{min} for relative standards now given by

$$q^{min} = \frac{\sqrt{K}}{\sqrt{a + b(\bar{e}-1)^2}}$$

and q^{min} for credit trading given by

$$q^{min} = \frac{\sqrt{4bK - R^2}}{\sqrt{4ab}} \tag{16}$$

The two equations for q^{min} are found by setting long-run average costs equal to marginal costs and then using (14) and (4) to eliminate E and R or $\bar{e}$.

Absolute Standards With absolute standards, the government sets a limit $\bar{E}$ on emissions per firm. Since firms are identical in this model, the analysis of absolute standards is rather similar to the analysis of permit trading above. However, there is one difference in that the firm does not have to cover opportunity costs of emissions. Hence, with absolute standards, it must hold that

$$\pi = pq - aq^2 - b(q - \bar{E})^2 - K \geq 0 \tag{17}$$

It is clear that this is different from the long-run profit function for permit trading given by (11). Otherwise, the first order conditions derived for permit trading also hold under absolute standards, with the difference that R^p is replaced by a shadow price λ.

This also implies that q^{min} for absolute standards is different from the one under permit trading. In this case, q^{min} found by setting long-run average costs equal to marginal costs

$$q^{min} = \frac{\sqrt{K + b\bar{E}^2}}{\sqrt{a+b}}$$

Combined Trading The model can also be used to analyze the effects of combining permit and credit trading. With perfect competition, the only interesting case is the one where two sectors operating on different product markets are connected through emissions trading. If two sectors, from different countries for example, operating on the same product market would be connected through emissions trading, the sector regulated through permit trading would vanish because of its higher marginal production costs.

In the following, we assume that the two sectors are identical in all aspects, except that they operate on two different goods market, which have the same demand function, and that one sector is regulated through permit trading, while the other is regulated through credit trading. In the case of combined trading, an additional condition is needed, given by

$$n^c E^c - n^c q^c \bar{e}^c = n^p \bar{E}^p - n^p E^p$$

where the superscripts c and p denote the credit and permit sectors respectively. This condition merely says that total emissions should be equal to total allowable emissions. Using this condition, together with the first order conditions for profit maximization for both sectors given in (8), (9), (13) and (14) and inverse demand function (2), the price of emission quotas can be determined as

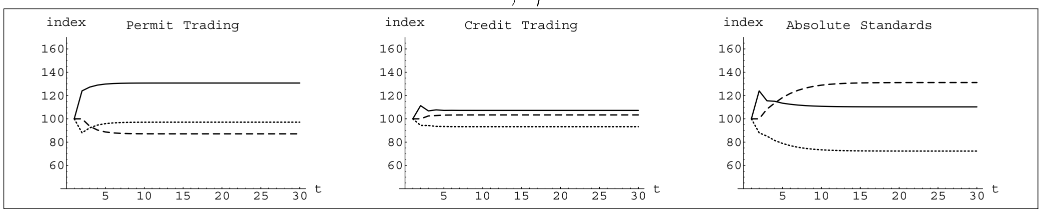
$$\begin{aligned} R = \quad & \Big\{-2b\left(4a^2 n^p \bar{E} + n^c n^p \beta\left[\left(\bar{e}-2\right)\alpha + n^p \bar{E}\beta\right)\right. \\ & \left. +2a\left(n^p\left(n^p\bar{E}\beta - \alpha\right) + n^c\left(\left(\bar{e}-1\right)\alpha + n^p\bar{E}\beta\right)\right)\right]\Big\} \\ & \Big/ \Big\{4a^2\left(n^c+n^p\right) + n^c n^p \beta\left(2b\left(2-2\bar{e}+\bar{e}^2\right) + \left(n^c+n^p\right)\beta\right) \\ & +2a\left(2b\left(n^p + n^c\left(\bar{e}-1\right)^2\right) + \left(n^c+n^p\right)^2\beta\right)\Big\} \end{aligned}$$

The quota price can then be used directly in the first order conditions to calculate q^c and q^p and the other variables.

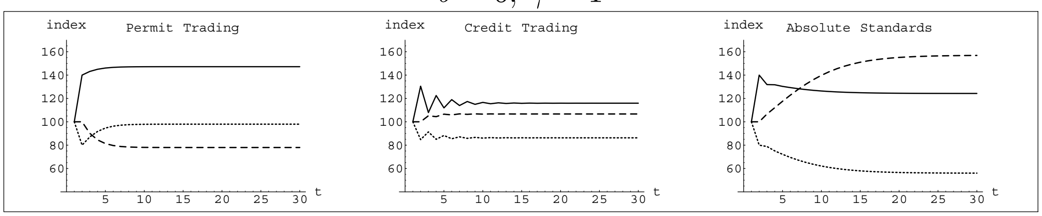
Figure 1: Perfect Competition, Myopic Government, Inelastic Demand

$a = 1,\ K = 1,\ \alpha = 6,\ \beta = 0.04$

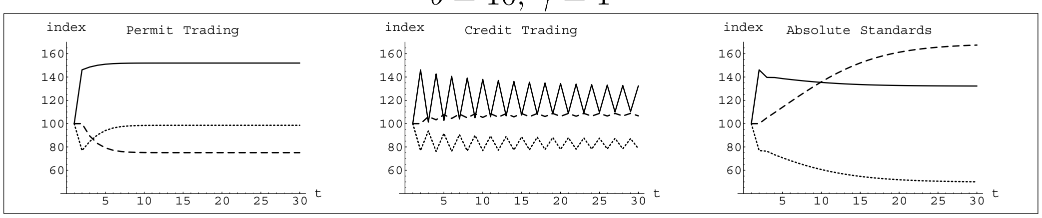
$b = 2,\ \gamma = 1$



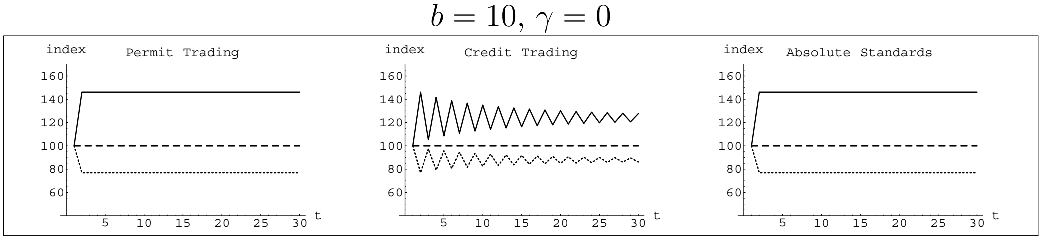
$b = 6,\ \gamma = 1$



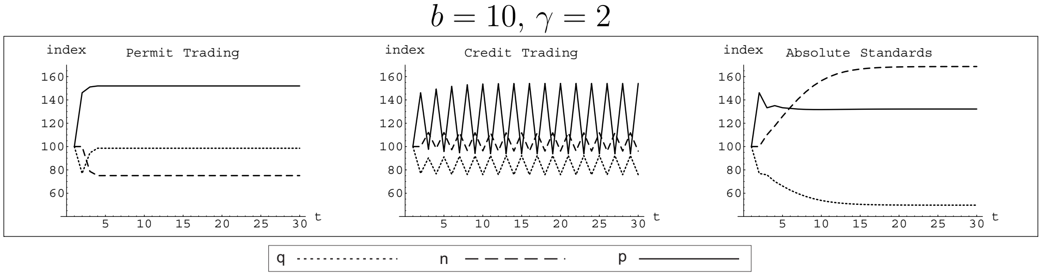
$b = 10,\ \gamma = 1$



$b = 10,\ \gamma = 0$



$b = 10,\ \gamma = 2$



The output of a firm in the permit sector is given by

$$q^p = \frac{\alpha - R}{2a + \beta n}$$

The output of a firm in the credit sector is

$$q^c = \frac{\alpha - R(1 - \bar{e})}{2a + \beta n}$$

Emissions in both cases are given by

$$E = q - \frac{R}{2b}$$

Also q^{min} changes for both cases. More precisely, q^{min} becomes identical for the two cases (see Boom and Dijkstra (2006))

$$q^{min} = q^{min} = \frac{\sqrt{4bK - R^2}}{\sqrt{4ab}}$$

The equations for emission quota price, output, emissions and zero profit output together with demand function (2), fully characterize the equilibrium in the combined system.

3.2 Simulation results

The results of the simulation[1] for perfect competition are reported in Figures 1 through 10. We will first discuss the case where the government behaves myopically. The simulation results for this are given in Figures 1 through 4. Figure 1 gives some cases with inelastic demand. The price elasticity of demand in the starting position without regulation is -0.5 in this case. Figures 2, 3 and 4 give cases with elastic demand. The price elasticity of demand in the starting position here is -1.25 for Figure 2 and -2 for Figures 3 and 4. Figures 5 through 7 give some of the same cases, but for combined trading.

In all cases, the initial condition is the same, with $q^n = 1$, $E^n = 1$, $p^n = 2$ and $n^n = 100$, where the superscript n denotes the no regulation case. Total emissions without regulation are then 100 and in all cases, except the last case in Figure 3, emissions are reduced by 30% giving a limit on total emissions

[1] The simulation algorithm was programmed in Fortran and is available from the author upon request

Figure 2: Perfect Competition, Myopic Government, Elastic Demand 1

$a = 1,\ K = 1,\ \alpha = 3.6,\ \beta = 0.016$

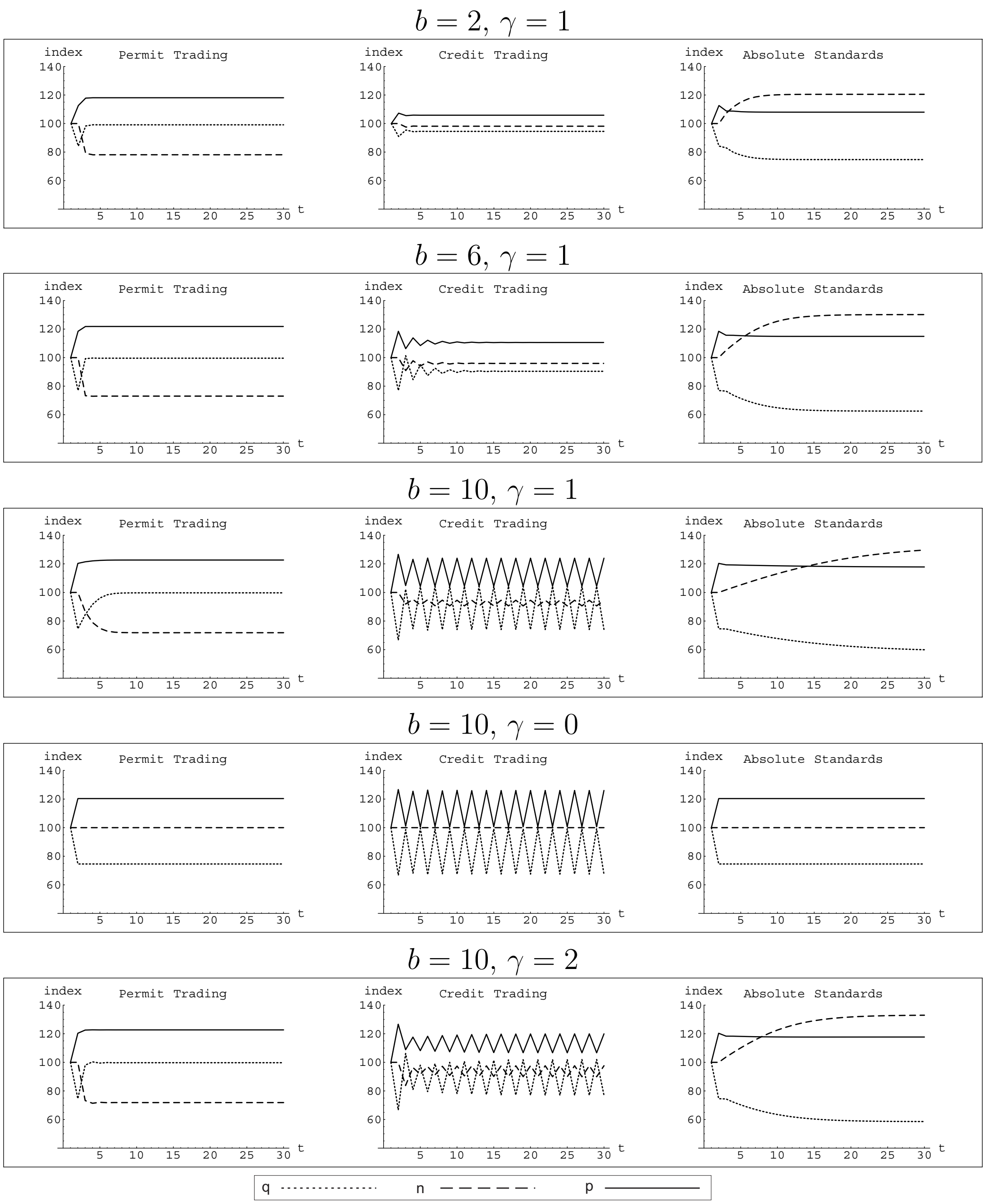
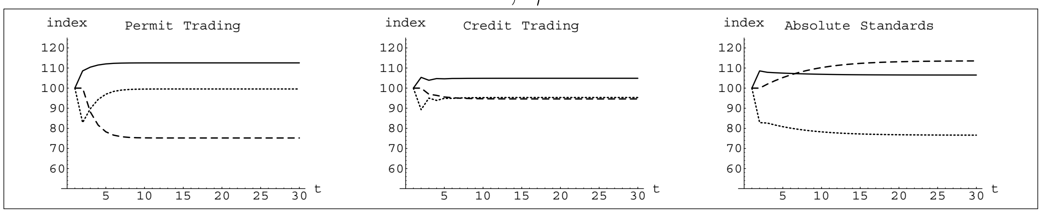


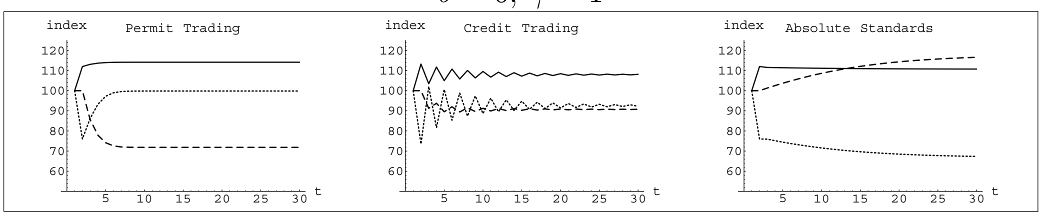
Figure 3: Perfect Competition, Myopic Government, Elastic Demand 2a

$a = 1,\ K = 1,\ \alpha = 3,\ \beta = 0.01$

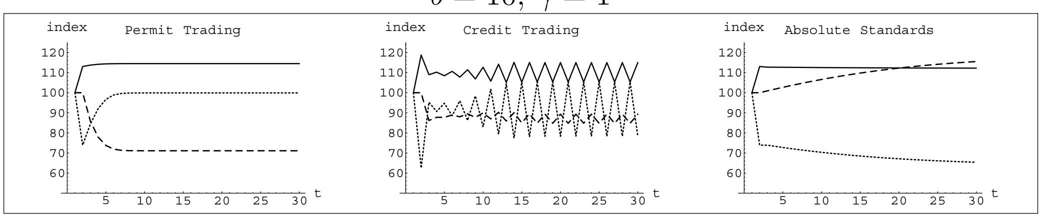
$b = 2,\ \gamma = 1$



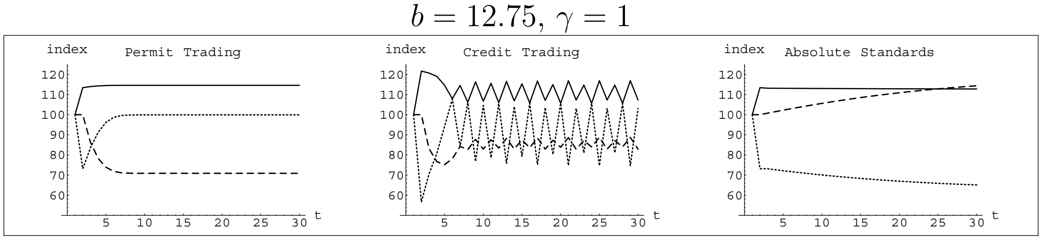
$b = 6,\ \gamma = 1$



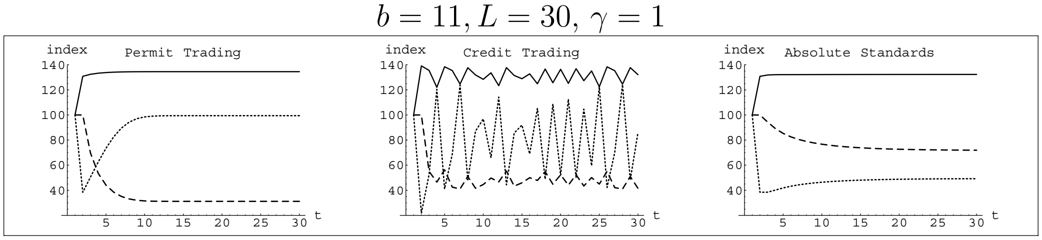
$b = 10,\ \gamma = 1$



$b = 12.75,\ \gamma = 1$



$b = 11, L = 30,\ \gamma = 1$



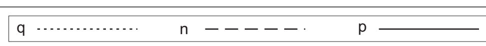
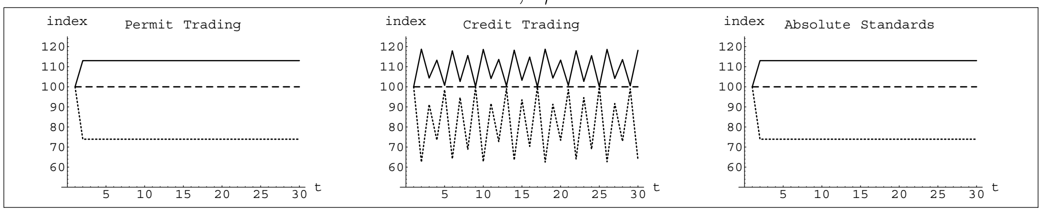
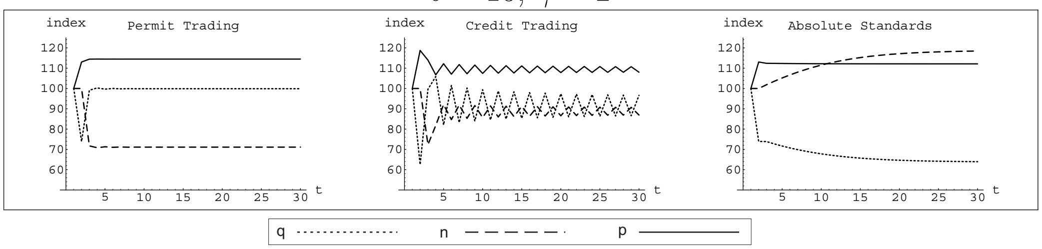


Figure 4: Perfect Competition, Myopic Government, Elastic Demand 2b

$$a = 1,\ K = 1,\ \alpha = 3,\ \beta = 0.01$$
$$b = 10,\ \gamma = 0$$



$$b = 10,\ \gamma = 2$$



of 70. Environmental policy is introduced in period two. In all figures, the dotted line gives output per firm, the drawn line gives price of output and the dashed line gives the number of firms. The values in the figures give the index relative to the no-regulation case.

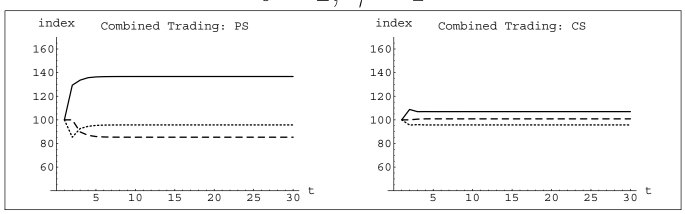
In the following, we will concentrate on the dynamic effects of regulation and pay little attention to the comparative statics effects. For the latter, at least for permit and credit trading, the reader is referred to Boom and Dijkstra (2006). One important aspect however is entry and exit of firms. Environmental regulation diminishes the efficient scale of operation of the firm. Whether environmental regulation then leads to entry or exit depends on the elasticity of demand. If demand is rather inelastic, total output will not change by much as a result of environmental regulation and firms will enter. When demand is elastic, total output will decrease by a large amount, and firms will exit.

A number of interesting features are shown in the figures. First of all, the transition from no regulation to regulation is often not very smooth, but may be rather volatile, especially with credit trading. Secondly, in most cases, credit trading (or relative standards) leads to less change in the long-run equilibrium than permit trading and absolute standards do. This was already shown in Boom and Dijkstra (2006). Thirdly, immediately setting the standard (relative or absolute) at its long-run equilibrium level may lead

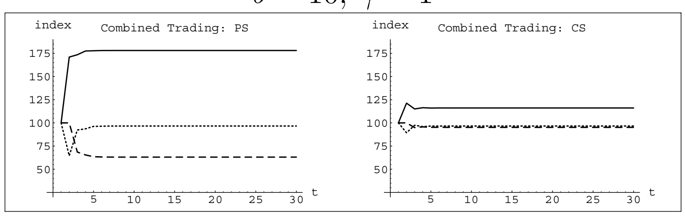
Figure 5: Perfect Competition, Myopic Government, Combined Trading, Inelastic Demand

$$a = 1,\ K = 1,\ \alpha = 6,\ \beta = 0.04$$

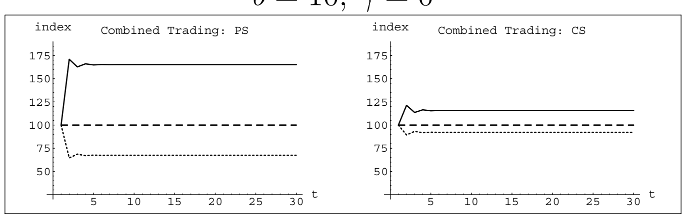
$$b = 2,\ \gamma = 1$$



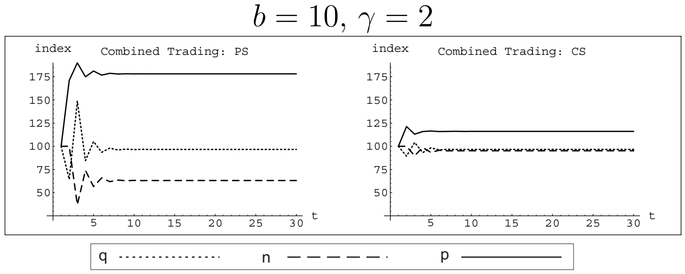
$$b = 10,\ \gamma = 1$$



$$b = 10,\ \gamma = 0$$



$$b = 10,\ \gamma = 2$$



to a longer transition period than myopic behavior by the government.

We start with the volatility in the market caused by regulation. As the figures show, there are basically two types of volatility. The first one is very short lived: the introduction of regulation can lead to a strong reaction in the first periods, whereafter the system more or less smoothly moves to the new equilibrium. This is clear in many of the cases, also when the optimal long-run standards are set from the first period onward.

The second type of volatility is of a more persistent nature, though only credit trading (relative standards) is prone to this type of volatility. Whether the system becomes volatile depends on several factors, such as the elasticity of demand, marginal costs of abatement, the rate of adjustment by firms (given by γ), and government policy. As is clear from a comparison of the figures, there is more volatility with credit trading when demand is elastic and when marginal abatement costs are high. The clearest case is given in Figure 3. Here permit trading and absolute standards give a more or less smooth transition path after the initial shock. However, with credit trading, the system becomes more volatile the higher marginal abatement costs become. For $b = 2, \gamma = 1$, credit trading shows a rather smooth path with little divergence from the no regulation case. However, when b becomes larger, the system shows two-period bifurcation ($b = 10, \gamma = 1$) and four-period bifurcation ($b = 12.75, \gamma = 1$). Putting more strain on the system by setting a lower total ceiling makes the system become chaotic ($b = 11, L = 30, \gamma = 1$). Hence, in these cases, the system never reaches an equilibrium. Unfortunately, the model could not be solved for very high elasticity of demand and high marginal abatement costs. However, the higher marginal abatement costs, the more volatile the system also becomes here.

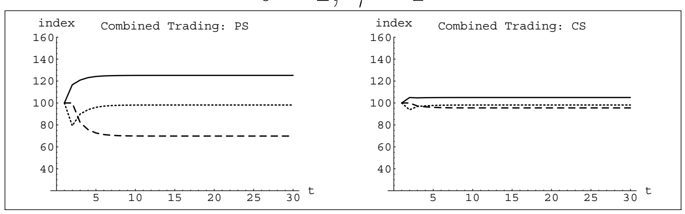
Chaos can arise when there is a non-linear relationship between a variable in a certain period and the same variable in the previous period (see Baumol and Benhabib 1989 and Shone 2002, Ch.7). In our model, there are two relationships that make a connection between the current and the previous value of a variable: the entry/exit condition given in (5) and government policy as given by how the standards are set (equations (3) and (4)). A glance at (5) shows that the entry/exit rule gives a linear relationship between the current and the previous number of firms, so that this cannot be the cause of chaos in the model. For government policy, the relationship is different between credit trading (and relative standards) on the one hand and absolute standards and permit trading on the other hand. For credit trading with myopic standard setting we find from (15) and (4)

$$\bar{e}_t = \frac{\beta}{\alpha} L + \frac{2L\left(a + b\left(\bar{e}_{t-1} - 1\right)^2\right)}{\alpha n_{t-1}} \tag{18}$$

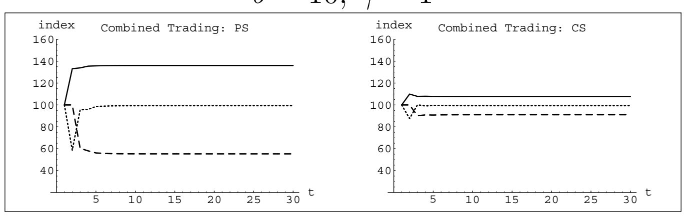
Figure 6: Perfect Competition, Myopic Government, Combined Trading, Elastic Demand 1

$$a = 1,\ K = 1,\ \alpha = 3.6,\ \beta = 0.016$$

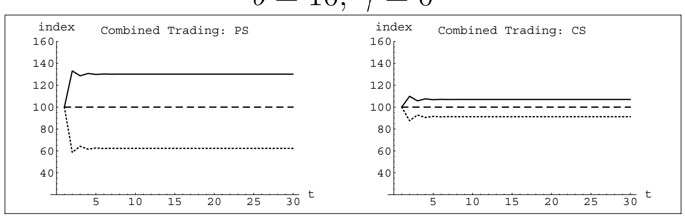
$$b = 2,\ \gamma = 1$$



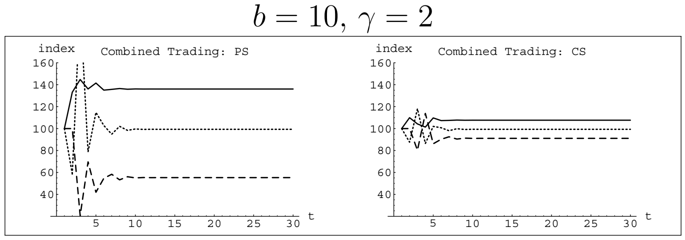
$$b = 10,\ \gamma = 1$$

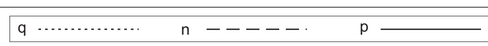


$$b = 10,\ \gamma = 0$$



$$b = 10,\ \gamma = 2$$





while for permit trading (if they are grandfathered) and absolute standards we find from (10) and (3)

$$\bar{E}_t = \frac{L}{n_{t-1}\left(1+\gamma\left(\frac{q_{t-1}}{q_{t-1}^{min}}-1\right)\right)} \tag{19}$$

Equation (18) shows that under myopic standard setting there is a nonlinear relationship between the current and previous relative standard, while (19) shows that there is a linear relationship for absolute standards and permit trading. Hence, only with credit trading and myopic setting of the relative standard the system can become chaotic. Whether there will be chaos under credit trading (and relative standards) depends on the values of the parameters, which is also clear from the figures.

The more elastic demand is, the more output will decrease as a result of the introduction of a given level of environmental regulation. With relative standards, this can lead to volatility as was mentioned above. Since the government is myopic, it sets the initial relative standard too strict. Firms react by reducing output by more than would be necessary to meet the overall emission limit. Then, in the next period, the government sets a too lax standard since it sets the standard based on output in the first period after regulation, leading to too high output. The higher the elasticity of demand, the larger the swings in output will be. But then, the government will also set a standard that is further from the correct standard in the initial periods. These effects are magnified with higher marginal abatement costs, since the higher marginal abatement costs are, the larger the reduction in output as a result of environmental regulation. As the figures show, these effects can reinforce each other such that the volatility becomes permanent, and even leads to chaos. It has to be noted though, that chaos is only found at rather extreme values of some of the parameters. Hence, in Figure 2, chaos is found with price elasticity of demand equal to -2 at the starting point and 70% emission reduction.

Entry and exit of firms leads to a movement in the opposite direction from the one following from the shifts in environmental regulation with a myopic regulator. With inelastic demand, higher speed γ of adjustment by firms then leads to higher volatility under credit trading, while with elastic demand, it dampens the volatility caused by shifts in the relative standard. For inelastic demand, we give cases with $\gamma = 0$ (no entry or exit) and $\gamma = 2$ in the last two boxes of Figure 1. With $\gamma = 0$, volatility gradually decreases. However, with $\gamma = 2$ there is high volatility under relative standards. This is a result of the high levels of entry and exit by firms. Figures 2 and 4 show that under credit trading and elastic demand volatility is high when there is no entry and exit ($\gamma = 0$). The higher the speed of entry, the lower the volatility subsequently becomes. To see why this is, start at period two where environmental policy is introduced. The government sets a relative standard based on the output level without environmental regulation. One of the results is that output decreases, and hence, the standard was set too tight. At the same time, profits are negative. Then in period three the government will calculate the relative standard anew, but will now set it too lax since output was very low in the first period with regulation. This will lead to a higher output level in period three. Without exit or entry, this would lead to a higher than optimal total output level. However, because profits were negative in period two, firms will exit in period three and hence total output will not increase by as much as it would have done if the number of firms was fixed. Hence, the exit of firms dampens the volatility in the system.

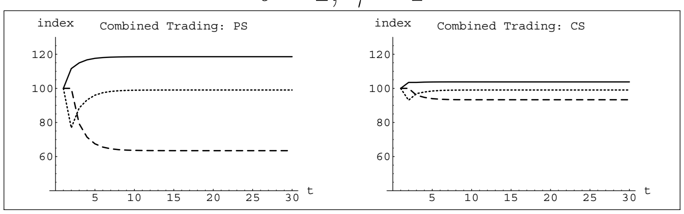
Combining the permit and credit trading in general gives a more smooth transition. A higher speed of entry and exit under combined trading always leads to more volatility as the last boxes in Figures 4 through 6 show.

We now turn to the case where the government sets the long-run equilibrium standards from the start. The results are given in Figures 8 through 10. For permit trading, the case where policy is set optimally from the start is identical to the myopic case, therefore, in Figures 8 through 10 we only give the trajectories for credit trading and absolute standards. The result is that setting a constant standard will give a smooth transition to the new equilibrium, but may lead to a longer transition period than setting a new standard in every period. Again, the result is dependent on the elasticity of demand. Comparing Figure 1 and Figure 8, it is clear that setting a fixed standard gets the system quicker to the new equilibrium. However, as demand becomes more elastic, the difference becomes smaller. In the first case given in Figures 2 and 9, with $b = 2, \gamma = 1$, it takes 22 periods for the industry under credit trading to reach equilibrium with both myopic and constant standards. For absolute standards, it takes 54 periods with myopic standards and 46 with fixed standards in the same case. With $b = 10, \gamma = 1$ credit trading does not lead to a stable equilibrium, so nothing can be said about the time it takes to reach the equilibrium. For absolute standards however, it takes 136 periods to reach a stable equilibrium with myopic standards, and 133 periods with constant standards. Hence, in this case, myopic and constant standards lead to virtually the same length of approach path to the new stable equilibrium, if such an equilibrium exists. In the second case with elastic demand, given in Figures 3 and 10, it takes longer to reach the new stable equilibrium with constant standards than with myopic standards. For example, with $b = 2, \gamma = 1$ it takes 30 periods for credit trading to reach the new equilibrium with myopic standards, while it takes 36 periods with

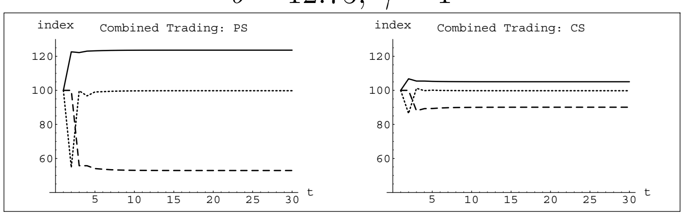
Figure 7: Perfect Competition, Myopic Government, Combined Trading, Elastic Demand 2

$$a = 1,\ K = 1,\ \alpha = 3,\ \beta = 0.01$$

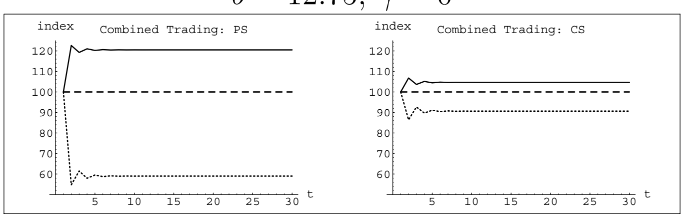
$$b = 2,\ \gamma = 1$$



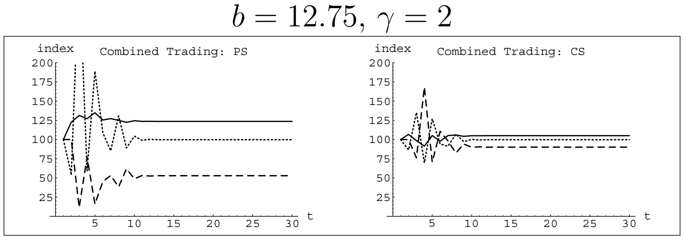
$$b = 12.75,\ \gamma = 1$$



$$b = 12.75,\ \gamma = 0$$



$$b = 12.75,\ \gamma = 2$$



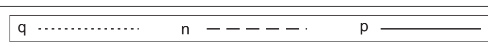
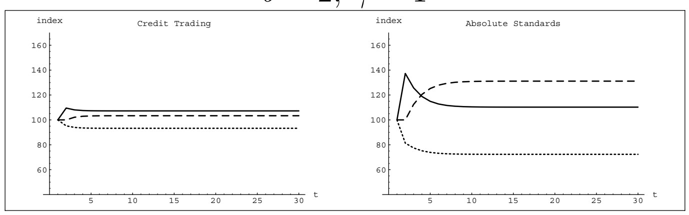


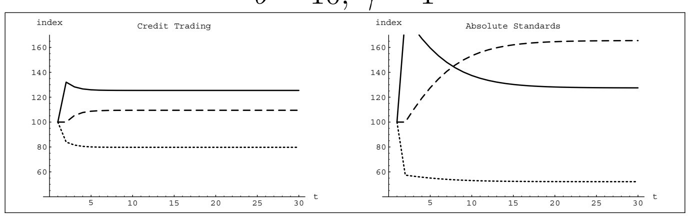
Figure 8: Perfect Competition, Constant Standards, Inelastic Demand

$a = 1,\ K = 1,\ \alpha = 6,\ \beta = 0.04$

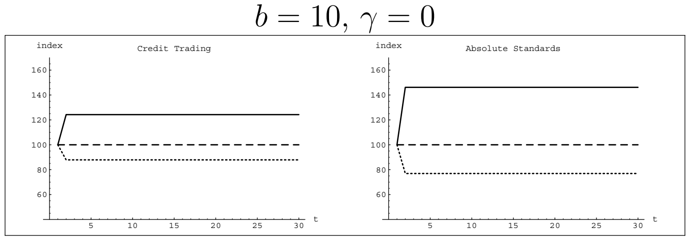
$b = 2,\ \gamma = 1$



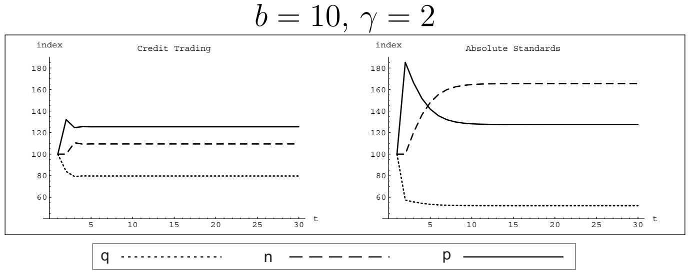
$b = 10,\ \gamma = 1$



$b = 10,\ \gamma = 0$



$b = 10,\ \gamma = 2$



constant standards. For absolute standards, it takes 69 periods with myopic standards and 71 with constant standards. In the case with $b = 12.75, \gamma = 1$, nothing can be said for credit trading because it does not lead to a a stable equilibrium with myopic standards. However, for absolute standards it takes 210 periods to reach the equilibrium with myopic standards and 236 periods with constant standards.

With constant standards, a high speed of entry and exit only leads to more volatility under inelastic demand. The reason for this is that with inelastic demand, total output at first decreases by too much when the optimal standard is set from the start, while with elastic demand, the market adjusts more gradually. With inelastic demand then, the initial spike is sustained and sometimes amplified by entry and exit.

Unfortunately, the model could not be solved for combined trading and constant standards. Therefore, no results for combined trading with constant standards are reported.

4 Imperfect competition

In this section, we give the case with oligopoly. In subsection 4.1 the discrete time model is given for the various types of regulation. In subsection 4.2, the simulation results of the transition phase are presented and discussed.

4.1 Regulation scenarios

No Regulation The no-regulation case is used as a starting point for the analysis and as a benchmark to measure changes against. We are therefore only interested in the long-run equilibrium, so no dynamics are incorporated in this stage. Assuming that all firms are identical and keeping the cost function (1), profits are given by

$$\pi_i = p(Q)q_i - aq_i^2 - b(q_i - E_i)^2 - K$$

where $Q = \sum_{i=1}^{n} q_i$. Using the demand function (2), the first order conditions are

$$\frac{\partial \pi_i}{\partial q_i} = \alpha - \beta Q - \beta q_i - 2aq_i - 2b(q_i - E_i) = 0$$

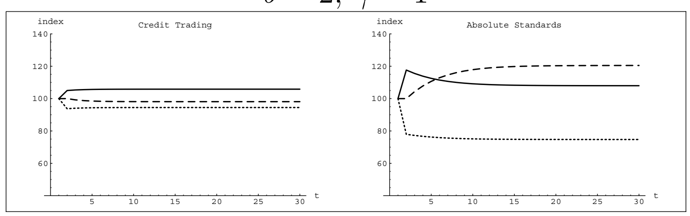
$$\frac{\partial \pi_i}{\partial E_i} = 2b(q_i - E_i) = 0 \quad \Rightarrow \quad q_i = E_i$$

With imperfect competition, firms can earn a profit, even in the long run. However, the number of firms need not be constant over time. The long-run

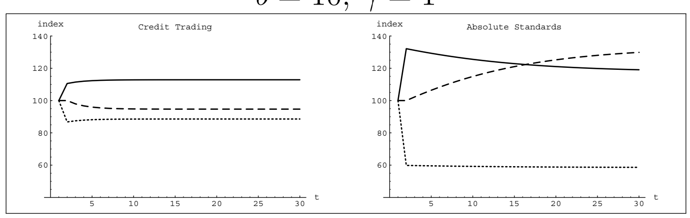
Figure 9: Perfect Competition, Constant Standards, Elastic Demand 1

$$a = 1,\ K = 1,\ \alpha = 3.6,\ \beta = 0.016$$

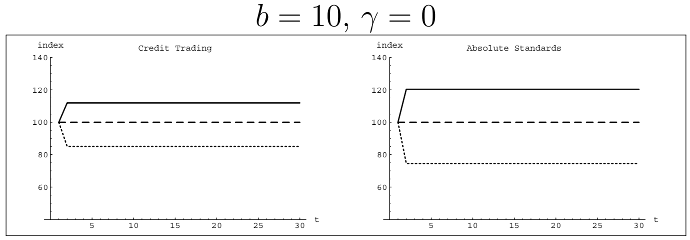
$$b = 2,\ \gamma = 1$$



$$b = 10,\ \gamma = 1$$



$$b = 10,\ \gamma = 0$$



$$b = 10,\ \gamma = 2$$

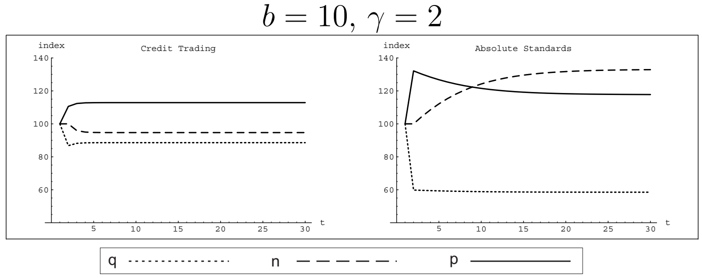
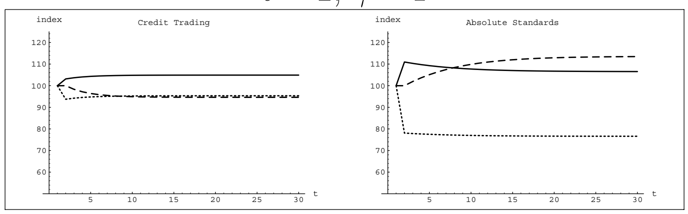


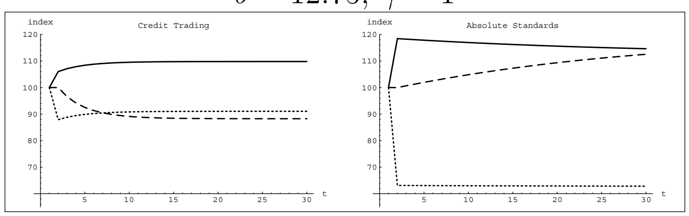
Figure 10: Perfect Competition, Constant Standards, Elastic Demand 2

$$a = 1,\ K = 1,\ \alpha = 3,\ \beta = 0.01$$

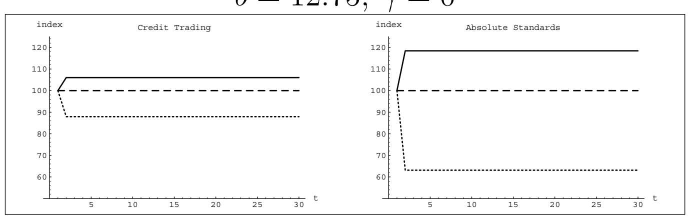
$$b = 2,\ \gamma = 1$$



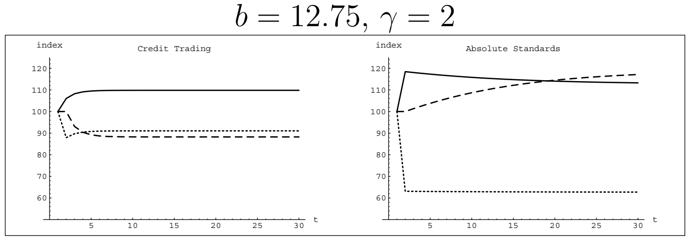
$$b = 12.75,\ \gamma = 1$$

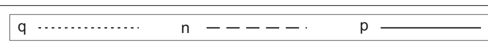


$$b = 12.75,\ \gamma = 0$$



$$b = 12.75,\ \gamma = 2$$





equilibrium conditions with imperfect competition are that all firms in the market should at least cover their costs, i.e., $\Pi_i \geq 0$ and that entry should not be profitable. Thus:

$$\pi_i(n^*) \geq 0 \quad \text{and} \quad \pi_i(n^*+1) < 0$$

where n^* is the equilibrium number of firms in the market. The equilibrium output level per firm is then given by

$$q_i = \frac{\alpha}{2a + (1+n^*)\beta}$$

Permit Trading With permit trading, the government puts a limit L on total emissions, giving an initial distribution of permits per firm of $\bar{E} = L/n$. The profit function for the firm then becomes:

$$\pi = p(Q)q_i - aq_i^2 - b(q_i - E_i)^2 - K - R^p(E_i - \bar{E})$$

Firm i assumes that $Q_{-i,t} = Q_{-i,t-1}$, where

$$Q_{-i} = \sum_{j=1, j\neq i}^{n} q_j$$

The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q_i} = \alpha - \beta(q_i + Q_{-i,t-1}) - \beta q_i - 2aq_i - 2b(q_i - E_i) = 0 \tag{20}$$

$$\frac{\partial \pi}{\partial E_i} = 2b(q_i - E_i) - R^p = 0$$

Since we have assumed that firms are identical, emissions after trading will be $E_i = L/n$. Solving for q_i from (20) gives

$$q_i = \frac{2b(L/n) + \alpha - \beta Q_{-i,t-1}}{2\,(a + b + \beta)}$$

Also under imperfect competition a firm regulated through permit trading must cover the opportunity costs of emissions. Therefore, it must hold that

$$\pi_i = p(q_i + Q_{-i,t-1})q_i - aq_i^2 - b(q_i - E_i)^2 - K - R^p E_i \geq 0$$

The equilibrium number of firms in the market, n^* is the smallest number of firms for which it holds that $\sum_{i=1}^{n^*+1} \pi_i < 0$. This is found iteratively. Hence, in the model, the number of firms in every period is increased from 2 to the number where profits are lower than zero. Then the number of firms in the market is the latter number of firms minus 1.

Credit Trading and Relative Standards Also here, the analysis of credit trading and relative standards is identical. Therefore, I concentrate on credit trading. With credit trading, the profits of a firm become

$$\pi_i = p(Q)q_i - aq_i^2 - b(q_i - E_i)^2 - K - R^c(E_i - \bar{e}q_i)$$

where $\bar{e} = L/Q_{t-1}$. Firm i assumes that $Q_{-i,t} = Q_{-i,t-1}$, so that the first order conditions for profit maximization are

$$\frac{\partial \pi_i}{\partial q_i} = \alpha - \beta(q_i + Q_{-i,t-1}) - \beta q_i - 2aq_i - 2b(q_i - E_i) + R^c\bar{e} = 0$$

$$\frac{\partial \pi_i}{\partial E_i} = 2b(q_i - E_i) - R^c = 0$$

The output level of firm i in period t is then given by

$$q_i = \frac{\alpha - \beta Q_{-i,t-1}}{2\left(a + b\left(\bar{e} - 1\right)^2 + \beta\right)}$$

Also under credit trading, the number of firms in the market is found through iteration.

Absolute Standards The analysis of absolute standards is identical to the one of permit trading except for two points. In the first place, there is no market for quotas, so there is no permit price under absolute standards. This means that R^p should be replaced with a shadow price λ. Secondly, under absolute standards, the firm does not have to cover the opportunity costs of emissions. Hence, the profit condition becomes

$$\pi_i = p(q_i + Q_{-i,t-1})q_i - aq_i^2 - b(q_i - E_i)^2 - K \geq 0$$

Combined Trading As with perfect competition, we can combine the two systems. From the first order conditions for permit and credit trading, we can derive for the emission level per firm

$$E_i^p = \frac{-\left(R^p(a+b+\beta) + b\left(\beta Q^p_{-i,t-1} - \alpha\right)\right)}{2b\,(a+\beta)}$$

$$E_i^c = \frac{-\left(R^c(a+b(1-\bar{e})+\beta) + b\left(Q^c_{-i,t-1}\beta - \alpha\right)\right)}{2b\,(a+\beta)}$$

Additionally, we need a condition on the total amount of emissions in both systems and a condition that the emission quota price will be the same in both segments of the market:

$$n^c E^c + n^p E^p = n^p \bar{E}^p + n^c q^c \bar{e}^c$$

$$R^p = R^c = R$$

Using these to solve for the price of emission quotas, we find

$$R = -\frac{b\left(2an^p\bar{E} + n^c\left(\bar{e}-1\right)\left(\alpha - \beta Q^c_{-i,t-1}\right) + n^p\left(\beta Q^p_{-i,t-1} - \alpha + 2\bar{E}\beta\right)\right)}{a\left(n^c+n^p\right) + b\left(n^p + n^c(\bar{e}-1)^2\right) + \beta\left(n^c+n^p\right)}$$

The emission quota price can then be used in the first order conditions to solve for q_i^p and q_i^c. These are given by

$$q_i^p = \frac{\alpha - R - \beta Q^p_{-i,t-1}}{2(a+\beta)}$$

$$q_i^c = \frac{\alpha + R(\bar{e}-1) - \beta Q^c_{-i,t-1}}{2(a+\beta)}$$

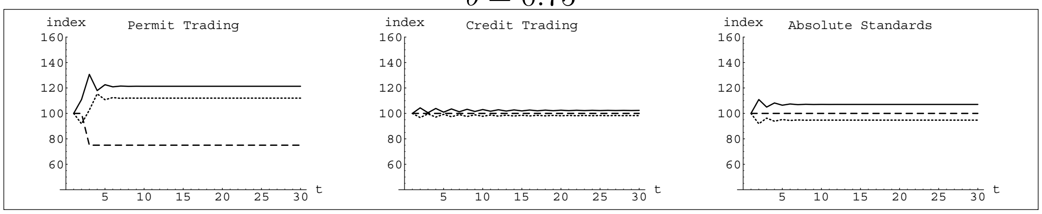
4.2 Simulation results

Simulation results are reported in Figures 10-13. The first three figures gives some cases where the standards are set myopically. In Figure 12, permit and credit trading are combined, while in Figure 13 the optimal long-run standard is set from the onset of regulation. In all cases, the initial conditions under no regulation are the same, with $q^n = 7.14$, $E^n = 7.14$, $p^n = 21.43$, $n^n = 4$ and profits of 2.04 in every period. Total emissions without regulation are 28.57 and the government wants to reduce this amount by 30%, leading to a limit on emissions of $L = 20$. The figures show the index of output per firm (dotted line), product price (drawn line) and the number of firms (dashed line) where the no regulation inices are set to 100.

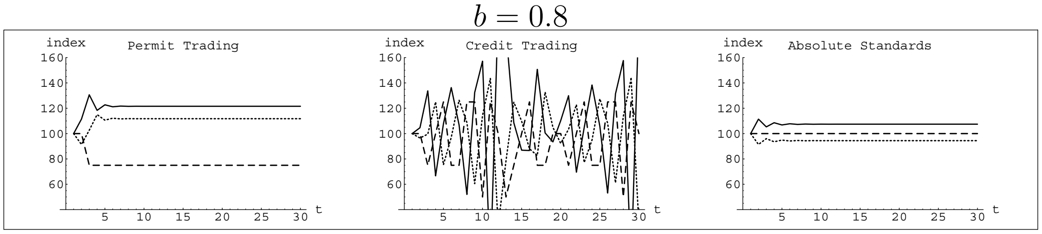
Figure 11: Imperfect Competition, Myopic Government

$a = 1,\ K = 100,\ \alpha = 50,\ \beta = 1$

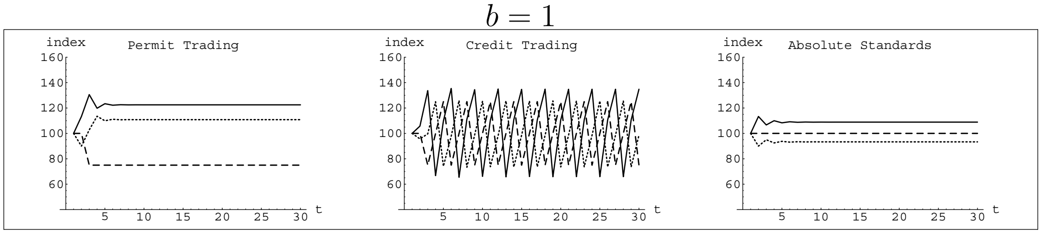
$b = 0.75$



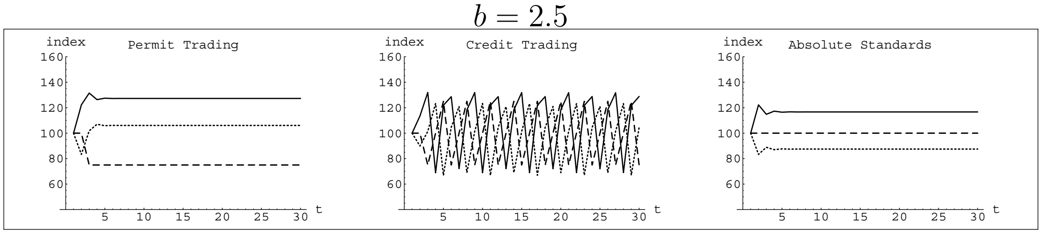
$b = 0.8$



$b = 1$



$b = 2.5$



$b = 3.4$

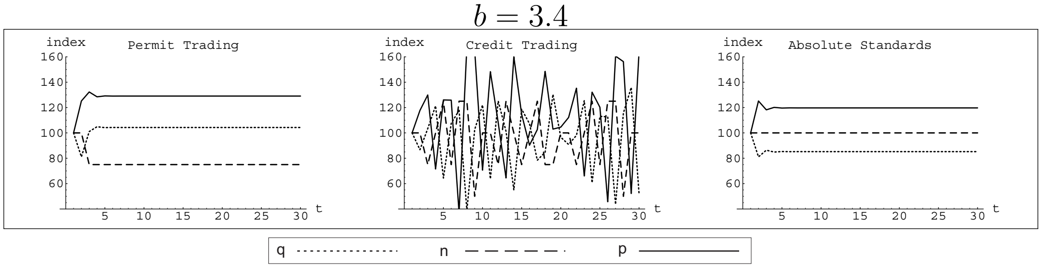


Figure 12: Imperfect Competition, Myopic Government

$a = 1$, $K = 100$, $\alpha = 50$, $\beta = 1$
$b = 3.4$

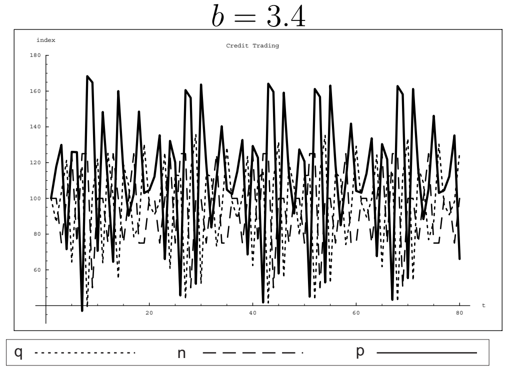
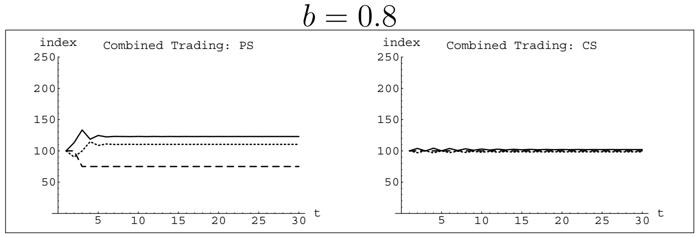
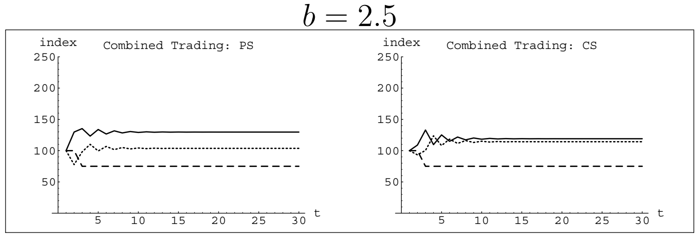


Figure 13: Imperfect Competition, Myopic Government, Combined Trading

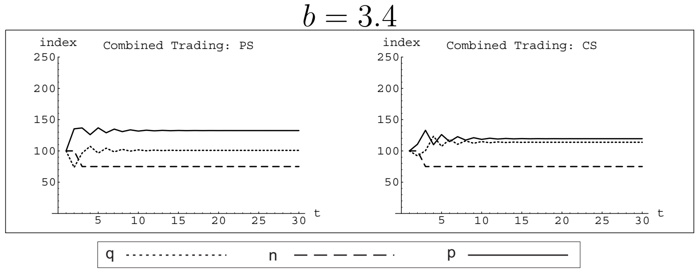
$a = 1$, $K = 100$, $\alpha = 50$, $\beta = 1$
$b = 0.8$



$b = 2.5$



$b = 3.4$



In a sense, one would expect more volatility in a market with oligopoly competition and Nash behavior than with perfect competition. The reason is that under these circumstances, any change will lead to reactions by the competitors. This is exacerbated by the assumption that firms set their output depending on their competitors' output in the previous period. This introduces a new lagged variable that can cause volatility. On the other hand however, changes in a oligopolistic market may be less pronounced and it is less likely that there will be changes in all variables in every period. For example, the number of firms may change as a result of the introduction of environmental regulation, but such a change often only occurs once or at most twice, at least under permit trading and absolute standards. This then has a dampening effect on the market.

These two forces, the one increasing volatility, the other decreasing it, seem to compensate each other more or less since the general results of the analysis under imperfect competition are rather similar to those under perfect competition. As with perfect competition, the market is more likely to be volatile under credit trading than under permit trading. As Figure 10 shows, the system quickly comes to equilibrium under low levels of b. However, already with $b = 0.8$, the system seems to become chaotic under credit trading. Interestingly, a higher b at first leads to a more structured form of volatility, whereafter the system becomes more chaotic again at $b = 3.4$. In Figure 11, the case of $b = 3.4$ under credit trading is given again, but now for a longer time period. It is clear from this figure, that there is high volatility, but that there also is some sense of regularity in the system. In this case, real chaotic behavior could not be produced. But then, the model could not be solved for higher levels of b than 3.4.

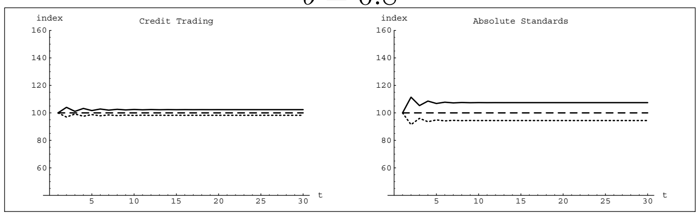
Combining the two systems leads to some volatility in both the permit and credit sector. However, the system always seems to go to an equilibrium. Hence, the volatility of the credit trading scheme spills over to the permit trading scheme, but eventually, the system eases down.

With imperfect competition, setting the standard at its long-run equilibrium value from the start leads to less volatility in the market at lower levels of b as can be seen from the case with $b = 0.8$ in Figures 10 and 13. However, at higher levels of b, the system becomes volatile again. This is a result from the interplay between the entry and exit of firms and the way firms set their production level. This shows that with imperfect competition, volatility can be a persistent phenomena under credit trading, even when the government sets a constant standard from the beginning of regulation. This in contrast to perfect competition where setting a constant standard always leads to a smooth adjustment to the new equilibrium, even with credit trading.

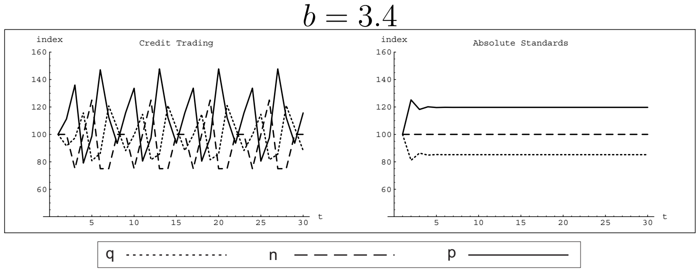
Figure 14: Imperfect Competition, Constant Standards

$$a = 1,\ K = 100,\ \alpha = 50,\ \beta = 1$$

$$b = 0.8$$



$$b = 3.4$$



5 Conclusion

In the economic literature, the performance of instruments for environmental regulation is mostly judged by their efficiency. Sometimes political, read distributional, effects are considered too. This paper takes into account that the economic impacts during the transition period from no regulation to the new equilibrium with regulation should be taken into account too. In particular the volatility of output, which is an indicator of fluctuations in employment, the price consumers pay for output and the number of firms since excessive entry and exit during the transition period are a waste the policy maker would rather want to avoid.

In the model resented, regular adjustment of standards can lead to volatility in the regulated industry when the instrument used is relative standards or credit trading. Such volatility is more likely to occur when demand is elastic, abatement costs are high and the emission reduction goal is rather ambitious. Swift entry and exit of firms increases the volatility with low elasticity of demand, but mitigates the level of volatility with high elasticity of demand. The volatility generated under credit trading in the dynamic model is due to the fact that there is a non-linear relationship between the relative standards in subsequent periods. With absolute standards, there is a linear relationship, while with permit trading, the government does not adjust the standard. The differences in how the standards are set explains why there is not much volatility with permit trading and constant standards, even when the government reacts myopically.

Of the types of regulation discussed in this paper, constant relative standards are the conventional approach in the European Union (van der Laan 2002) and also in the USA. Frequent retrospective adjustment of standards does not occur. The possibility that total emissions will end up above or below the long run target is simply accepted. Absolute standards or emission ceilings are only applied by exception. In contrast, emissions trading in various forms may have the future. Several programs of credit trading exist in the USA and the UK. The USA was also the first in starting a permit trading program for SO_2 emissions. The EU has just launched a permit trading scheme for CO_2 emissions. From the point of view of policy relevance, a comparison of credit trading and permit trading programmes to assess their performances during the transition stage from no regulation to the new equilibrium with regulation in particular in terms of volatility therefore is in place.

In all simulations of permit trading under perfect competition the number of firms and product price increases or decreases smoothly. Only output per firm overshoots its long-run equilibrium in the first periods after the introduction of regulation, but subsequently adjusts smoothly. With imperfect competition the adjustment is generally somewhat less smoothly, but basically the same as with perfect competition. With perfect competition and constant standards, credit trading leads to an at least equally smooth adjustment at with permit trading. However, with imperfect competition credit trading can lead to volatility in the market, even when the standard is set at its long-run optimal level from the start of the program.

These results suggest that under perfect competition differences in pains of adjustment are not likely to play a role in the choice between credit and permit trading or constant standards. Volatility would then only be a problem when the government uses credit trading and frequently adjusts the underlying relative standard. However, with imperfect competition, credit trading may lead to higher adjustment costs, even when the government does not adjust the underlying relative standard. In that case, permit trading would be the better choice.

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